# $M_{\rm BH}$–$\sigma$ relation for a Complete Sample of Soft X-ray Selected AGNs

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## ABSTRACT

We present black hole mass–bulge velocity dispersion relation for a complete sample of 75 soft X-ray selected AGNs: 43 broad line Seyfert 1s and 32 narrow line Seyfert 1s. We use luminosity and FWHM(H$\beta$) as surrogates for black hole mass and FWHM([OIII]) as a surrogate for the bulge velocity dispersion. We find that NLS1s lie below the $M_{\rm BH}$–$\sigma$ relation of BLS1s, confirming the Mathur *et al.* (2001) result. The statistical result is robust and not due to any systematic measurement error. This has important consequences towards our understanding of black hole formation and growth: black holes grow by accretion in well formed bulges, possibly after a major merger. As they grow, they get closer to the $M_{\rm BH}$–$\sigma$ relation for normal galaxies. The accretion is highest in the beginning and dwindles as the time goes by. Our result does not support theories of $M_{\rm BH}$–$\sigma$ relation in which the black hole mass is a constant fraction of the bulge mass/ velocity dispersion *at all times* or those in which bulge growth is controlled by AGN feedback.

*Subject headings:* galaxies: active - galaxies: bulges - galaxies: evolution - galaxies: formation - quasars:general

## 1. Introduction

Active galaxies are "active" because they accrete matter on to the supermassive black holes. However, whether the accretion leads to significant growth of the nuclear black hole has been a matter of some debate. New results on X-ray background and the better determination of local black hole mass density have led to the conclusion that indeed, black holes grow during their active phase (e.g. Barger et al. (2001); Aller & Richstone (2002); Yu & Tremaine (2002)).

The above result needs to be understood in the context of the observed tight correlation between the central black hole $M_{\rm BH}$ and the stellar velocity dispersion $\sigma_*$ of the bulge in a galaxy (e.g. Gebhardt et al. (2000a); Ferrarese & Merritt (2000); Merritt & Ferrarese (2001)). Measuring black hole masses using stellar and gas dynamics (Kormendy & Richstone (1995) and references therein), these authors found that log $M_{\rm BH}$ = $a + b\times\log(\sigma_*/\sigma_0)$ with $M_{\rm BH}$ in units of $M_\odot$ and $\sigma_0$=200 km s$^{-1}$. The slopes $b$ of this relation vary between $b = 3.75$ (Gebhardt et al. 2000a) and $b = 5.27$ (Ferrarese & Merritt 2000). Most recently, Tremaine et al. (2003) estimated $b = 4.02$ and $a = 8.13$ for a sample of 31 nearby galaxies. Interestingly, the above relation for normal galaxies also extends to active galaxies (Gebhardt et al. 2000b; Ferrarese et al. 2001).

The above two results imply that the formation and growth of the nuclear black hole and the bulge in a galaxy are intimately related, and several theoretical models have attempted to explain the observed $M_{\rm BH}$– $\sigma$ relation (e.g. Haehnelt (2003); Haehnelt et al. (1998); Adams et al. (2001) and King (2003)). To understand the link between the black hole and the bulge, it is important to determine whether (a) black hole mass is a constant fraction of the bulge mass, or bulge velocity dispersion, at all times, or (b) during some accreting phase, the $M_{\rm BH}$– $\sigma$ relation is not followed by

AGNs. The former can be obtained if, e.g., the growth of a black hole matches the growth of its surrounding bulge exactly during a merger. Alternatively, feedback from a black hole can limit the bulge growth. In case (b), the accretion history of a black hole is not tied to the bulge growth. It is still possible that today's highly accreting AGNs do lie on the $M_{\rm BH}$– $\sigma$ relation for normal galaxies, and may eventually leave the relation as their BHs grow. Or, today's highly accreting AGNs may lie below the $M_{\rm BH}$– $\sigma$ relation for normal galaxies, and would eventually reach the relation as the active BHs become dead. Indeed, in a recent model by Miralda-Escudé & Kollmeier (2003), which explicitly couples accretion with the stellar system in the bulge, the observed $M_{\rm BH}$– $\sigma$ relation is the final relation at the end of the accretion process.

It is of interest, therefore, to follow the tracks of AGNs on the $M_{\rm BH}$– $\sigma$ plane. Since black holes would grow fastest with high accretion rates, active galaxies with close to Eddington accretion are perhaps the best candidates. At low redshift, a lot of observational evidence suggests that narrow line Seyfert 1 galaxies (NLS1s; a subclass of Seyfert galaxies with full width at half maximum of H$\beta$ lines less than 2000 km s$^{-1}$(Osterbrock & Pogge 1985)) accrete at close to Eddington rate (e.g. Pounds et al. (1995); Grupe (2004) and references there in). Mathur et al. (2001) argued that NLS1s do not follow the $M_{\rm BH}$– $\sigma$ relation. This, however, was only a suggestive result because the sample size was small and neither the black hole masses nor the velocity dispersions were accurately measured. Wandel (2002) confirmed the Mathur *et al.* result with a sample of 55 AGNs (see also Bian & Zhao (2003)). On the other hand, Wang & Lu (2001) have argued that both BLS1s and NLS1s follow the $M_{\rm BH}$– $\sigma$ relation. Clearly, it is important to test whether NLS1s occupy a distinct region in the $M_{\rm BH}$– $\sigma$ plane using a large, homogenous sample. In this paper we present our results based on a complete sample of 110 soft X-ray selected AGN.

Note also that NLS1s are interesting objects as they occupy one extreme end of the "eigenvector 1" relation of AGNs (Boroson & Green (1992)). The most widely accepted paradigm for NLS1s is that they accrete at close to Eddington rate and have smaller black hole masses for a given luminosity compared to BLS1s. Finding their locus on the $M_{\rm BH}$–$\sigma$ plane is therefore a worthwhile experiment anyway as we will either find that occupy a distinct region compared to BLS1s or that they don't. The first option is interesting for the reasons discussed above. On the other hand if we find that NLS1s follow the $M_{\rm BH}$–$\sigma$ relation like the BLS1s, it has important implications towards our understanding of the AGN phenomenon. As noted above, we already have a good evidence for smaller BH masses of NLS1s, at a fixed luminosity. If they follow the $M_{\rm BH}$–$\sigma$ relation, it would imply that NLS1s preferencially reside in galaxies with bulges of smaller velocity dispersion. This would be a direct evidence for dependence of AGN properties on their large scale galactic environment.

In section 2 we discuss the sample selection and the methodology to determine the black hole masses using the widths of the H$\beta$ lines. Widths of the forbidden [OIII] lines are used as surrogates for bulge velocity dispersion. In section 3 we present the results and the discussion is in section 4.

## 2. Estimates of $M_{\rm BH}$ and $\sigma$

### 2.1. The Sample

The sample contains all bright soft X-ray selected AGN from the ROSAT All-Sky Survey (RASS, Voges et al. (1999)). The selection criteria are given in Thomas et al. (1998) and Grupe et al. (1999). About half of these sources are NLS1s (51 objects) and 59 are broad line seyfert 1s (BLS1s). NLS1s and BLS1s show similar distribution in their redshifts, luminosities and equivalent widths of H$\beta$ (Grupe et al. 2004). From this original sample of 110 AGNs, we removed all the objects in which [OIII] lines were severely unresolved leading to errors in the FWHM measurements, with S/N$<$ 3. This left us with a sample of 75 AGNs, 32 NLS1s and 43 BLS1s.

### 2.2. Black hole mass

Based on the reverberation mapping of the H$\beta$ line of 28 PG quasars, Kaspi et al. (2000) derived an empirical relation between the width of the H$\beta$ line and the central black hole mass. They found that log $M_{\rm BH}$ =5.17+log $R_{\rm BLR}$ + 2 $\times$ (logFWHM(H$\beta$) $-$ 3) with $M_{\rm BH}$ given in units of $M_\odot$ and FWHM(H$\beta$) given in units of km s$^{-1}$. $R_{\rm BLR}$ is the radius of the broad emission line region (BLR) and is larger for more luminous

sources: log $R_{\rm BLR} = 1.52 + 0.70 \times (\log\lambda L_{5100} - 37)$ where $R_{\rm BLR}$ given in units of light days, $L_{5100}$ is the monochromatic luminosity at 5100Å, and $\lambda L_{5100}$ is in units of Watts. This relation is well calibrated, albeit with some scatter, and can be used to estimate $M_{\rm BH}$ of active galaxies using FWHM(H$\beta$) and luminosity. Many authors have used it to derive $M_{\rm BH}$ of Seyfert galaxies and quasars (e.g. Laor (1998) and Wandel (1999)) and we do the same (except for NGC 4051, which is known not to follow the radius luminosity relation, and so we use the BH mass as measured by reverberation (Peterson et al. 2000)). For our sample, FWHM(H$\beta$) and optical luminosities are given in Grupe et al. (2004).

### 2.3. Velocity dispersion

The stellar velocity dispersion $\sigma_*$ in the bulge of a galaxy can be measured by the widths of the CaII triplet absorption features at 8498.0, 8542.1, and 8662.1 Å. In a sample of 85 AGN, Nelson & Whittle (1995, 1996) found a moderately strong correlation between $\sigma_*$ and FWHM([OIII]), the full width at half maximum of the [OIII]$\lambda$5007 line. Therefore, Nelson (2000) suggested that the FWHM([OIII]) can be used as a surrogate of $\sigma_*$ with $\sigma_* \approx \sigma_{\rm [OIII]} = {\rm FWHM([OIII])}/2.35$. This result was confirmed by Boroson (2003), who stated that the [OIII] width can predict the black hole mass to a factor of 5 assuming the $M_{\rm BH}-\sigma$ relation. Shields et al. (2003) used the FWHM[(OIII)] as a surrogate of the bulge stellar velocity dispersion $\sigma_*$ for a large sample of AGN and concluded that it can be extended even to redshifts as high as z≈3. We also use FWHM([OIII]), given in Grupe et al. (2004), as an estimate of $\sigma_*$ for our sample.

## 3. Results

Fig. 1 plots the black hole mass derived from FWHM(H$\beta$) vs. velocity dispersion $\sigma$ derived from the FWHM([OIII]) for our sample of 75 AGNs. The solid line is the relation of Tremaine et al. (2003) obtained for normal galaxies. Clearly there is a large scatter around this relation, and most likely implies that the surrogates do not reproduce $M_{\rm BH}$ and $\sigma$ accurately. A comparison of the black hole masses derived from our data with reverberation mapping results (Kaspi et al. (2000); Peterson et al. (2000); Wandel (1999); Kollatschny (2003)) shows that the black hole masses agree on average, with a random scatter of about 0.2 dex. Considering the scatter in the radius–luminosity relation, variability and the unknown geometry of the broad line region, we conservatively estimate the error on BH mass measurement to be 0.5 dex.

The observational error in $\sigma$ depends on the strength of the [OIII] line. As shown in Grupe (2004) there is a strong anti-correlation between the FWHM([OIII]) and equivalent width of [OIII]. Plus the weaker the [OIII] line the stronger the FeII emission becomes (e.g. Boroson & Green (1992); Grupe (2004)) which makes the line measurements in the objects with broader [OIII] more uncertain than those with narrow [OIII] emission. The errors of the FWHM([OIII]) are given in Grupe et al. (2004) and are of the order of 0.2 dex. Clearly, errors on both quantities, $M_{\rm BH}$ and $\sigma$ are large for individual objects. However, we are interested in statistical differences in the two populations, of a large number of BLS1s and NLS1s, and not on exact values of individual sources.

Figure 1 shows that BLS1s and NLS1s occupy two distinct regions in the $M_{\rm BH}-\sigma$ plane. For a given velocity dispersion NLS1s tend to show smaller smaller black hole masses than BLS1s. If true, this is an important result. However, before coming to that conclusion, we have to make sure that the result is not spurious. A spurious result may be obtained if the black hole masses of NLS1s are systematically underestimated or if their velocity dispersions are systematically overestimated relative to BLS1s. We will check these two cases below.

*Are the black hole masses of NLS1s wrong?* Fig. 2 shows the cumulative fraction of the distributions of the inferred black hole masses of NLS1 (solid line) and BLS1s (dashed line) for a Kolmogorov-Smirnov (KS) test. The plot clearly shows that NLS1 and BLS1s have different distributions of the black hole masses. In general, more luminous AGNs have higher black hole masses, but for a given luminosity NLS1s have black hole masses about an order of magnitude lower than BLS1s (note that the BLS1s and NLS1s in our sample have similar luminosities; §2.1). This result confirms earlier findings of, e.g. Wandel & Boller (1998) and Peterson et al. (2000) and is

unlikely to be spurious. In fact, NLS1s have narrower broad emission lines because of the smaller black hole masses. If they had masses similar to the BLS1s, their BLRs would have to be relatively farther away from the black hole. This, however, is not the case; Peterson et al. (2000) have found that NLS1s and BLS1s follow the same relation between the BLR size and luminosity. We thus conclude that there is a real difference in the black hole mass distribution of BLS1s and NLS1s.

*Are the estimates of velocity dispersion wrong?* If FWHM([OIII]) is not a good surrogate, our estimates of $\sigma$ may well be wrong. This could produce dichotomy between NLS1s and BLS1s if $\sigma_{[OIII]} - \sigma_*$ is systematically different for the two classes. The first indication that this is not the case comes from the similarity of distribution of their $\sigma$ (Fig. 3). A KS test shows that the two classes do not show any significant difference.

One might overestimate the [OIII] widths if the spectral resolution is low and lines are not resolved. We correct for the instrumental line broadening in our measurements (Grupe et al. 2004). Moreover, if resolution was a problem, we would have seen a clustering of line widths close to the instumental line widths. Instead, we observe a wide range of widths, and the distribution of widths for BLS1s and NLS1s is similar. This implies that any problem with resolution is not artificially increasing the line widths of NLS1s only.

One problem which might affect NLS1s only is the strong FeII emission close to O[III]$\lambda$5007 emission line. For our entire sample, FeII contribution has been subracted before making measurements on the [OIII] lines (Grupe et al. 2004). If FeII contribution was systematically undersubtracted, it will lead to overestimation of [OIII] line widths. With this in mind, we re-examined the FeII subtracted spectra of all the NLS1s in our sample. We found that FeII emission was not undersubtracted, and may even be slightly oversubtracted, in all but but two cases. Deleting these two objects with poorer S/N from our sample does not change the statistical result.

A more detailed look at many [OIII] lines shows that they have blue asymmetry in a number of AGNs (e.g. Gonçalves et al. (1999); Leighly (2000)), possibly resulting from outflows. These observations need further scrutiny since the asymmetry might have resulted in erronously large measurements of FWHM([OIII]). (Note, however, that a part of the blue asymmetry may be a result of oversubtracting the FeII emission from the red part of the line.) To correct for this possible problem, we re-measured the width of the [OIII] line as 2× half width at half maximum of the red part of emission line. While the new measurements reduce individual values of $\sigma$, the BLS1s and NLS1s still ccupy distinct regions in the $M_{\rm BH}$– $\sigma$ plot. This is clearly seen from figure 4 which plots the cumulative distribution of the ratio $M_{\rm BH}/\sigma$ for BLS1s and NLS1s. The two classes are significantly different, with formal K-S test probability of being drawn from the same population $< 0.001$.

## 4. Discussion

In this paper we present distribution of black hole masses and bulge velocity dispersions for a comple sample of AGNs. Black hole masses are estimated from a well calibrated relation between the width of the H$\beta$ emission line, luminosity and $M_{\rm BH}$. Bulge velocity dispersion is estimated from the width of the narrow [OIII] emission line. Neither of these are accuarate measurements of the two quantities and errors on the values of $M_{\rm BH}$ and $\sigma$ for individual objects are large. The results presented here are therefore statistical, and compare the broad distributions of the two classes of AGNs, the BLS1s and the NLS1s.

We find that BLS1s and NLS1s occupy two distinct regions in the $M_{\rm BH}$– $\sigma$ plane. This does not appear to be a result of systematically underestimating black hole masses or systematically overestimating the [OIII] line widths of NLS1s. This might be still a spurious result if the narrow emission line region of NLS1s is somehow much closer to the center of the galaxy and so does not trace the bulge velocity dispersion. While we cannot rule out this possibility, there are no observations supporting this fact either.

After carefully investigating all the options, we come to the conclusion that the result is unlikely to be spurious in that NLS1s and BLS1s do have different ratios of black hole mass to bulge velocity dispersion. So if BLS1s follow the $M_{\rm BH}$–$\sigma$ relatation for normal galaxies, then NLS1s do not. Needless to say, this result will have to be confirmed with accurate measurements of black hole masses and bulge velocity dispertions. If con-

firmed, it has important consequences towards our understanding of black hole formation and growth. We find that the black hole mass is not a constant fraction of the bulge mass or of bulge velocity dispersion *at all times*. In other words, growth of a black hole by accretion does not match the growth of its surrounding bulge exactly or the accretion process itself does not increase the bulge velocity dispersion. Thus, our results are also inconsistent with the models of $M_{\rm BH}$–$\sigma$ relation in which feedback from a black hole controls the growth of the bulge. Our resuls support a scenario in which black holes grow by accretion in well formed bulges, possibly after a major merger. Perhaps, the surge in accretion is a result of that merger itself. As they grow, they get closer to the $M_{\rm BH}$–$\sigma$ relation for normal galaxies. The accretion rate is highest in the beginning and dwindles as the time goes by. This scenario is consistent with the recent theoretical model of Miralda-Escudé & Kollmeier (2003) in which the $M_{\rm BH}$–$\sigma$ relation is the final state at the end of the accretion process. The observation that the broad line Seyfert 1s lie close to the $M_{\rm BH}$–$\sigma$ relation then tells us that the black hole mass growth at low accretion rate is not significant. This scenario is also consistent with the proposal of Grupe et al. (1999) and Mathur (2000) that NLS1s are younger members of the Seyfert population. Presumably, the insight we have got from studying the Seyfert galaxies is also applicable to quasars. To understand further the history of BH and bulge growth, similar observations at high redshift would be valuable.

We thank Jordi Miralda-Escudé, Brad Peterson, Rick Pogge, Greg Shields, David Weinberg and Bev Wills for helpful discussions. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.

## REFERENCES

Adams, F.C., Graff, D.S., & Richstone, D.O

Aller, M.C., & Richstone, D., 2002, AJ, 124, 3035

Barger, A.J., Cwie, L.L., Bautz, M.W., Brandt, W.N., Garmire, G.P., Hornschemeier, A.E., Ivison, R.J., & Owen, F.N., 2001, AJ, 122, 2177 ., 2001, ApJ, 591, 125

Bian, W., & Zhao, Y., 2003, MNRAS in press, astro-ph/0309701

Boroson, T.A., & Green, R.F., 1992, ApJS, 80, 109

Boroson, T.A., 2002, ApJ, 565, 78

Boroson, T.A., 2003, ApJ, 585, 647

Ferrarese, L., & Merritt, D., 2000, ApJ, 539, L9

Ferrarese, L., Pogge, R.W., Peterson, B.M., Merritt, D., Wandel, A., & Joseph, C.L., 2001, ApJ, 555, L55

Gebhardt, K., Bender, R., Bower, G., Dressler, A., Faber, S.M., et al., 2000, A&A, 539, L13

Gebhardt, K., Kormendy, J., Ho, L.C., Bender, R., Bower, G., et al., 2000, ApJ, 543, L5

Gonçalves, A.C., Veron, P., & Veron-Cetty, M.-P., 1999, A&A, 341, 662 Göttingen

Grupe, D., Beuermann, K., Mannheim, K., & Thomas, H.-C., 1999, A&A, 350, 805

Grupe, D., Wills, B.J., Leighly, K.M., & Meusinger, H., 2004, AJ, in press (Jan. 2004), astro-ph/0310027

Grupe, D., 2004, AJ, submitted

Haehnelt, M., 2003, Classical and Quantum Gravity, 20, S31

Haehnelt, M.G., Natarajan, P., & Rees, M.J., 1998, MNRAS, 300, 817

Kaspi, S., Smith, P.S., Netzer, H., Moaz, D., Jannuzi, B.T., & Giveon, U., 2000, ApJ, 533, 631

King, A., 2003, ApJL, 596, L27

Kormendy, J., & Richstone D., 1995, ARA&A, 33, 581

Kollatschny, W., 2003, A&A, 407, 461

Laor, A., 1998, ApJ, 505, L83

Leighly, K.M., 2000, ASP Conf. Series, 224, p293

Mathur, S., 2000, MNRAS, 314, L17

Mathur, S., Kuraszkiewicz, J., & Czerny, B., 2001, New Astronomy, Vol. 6, p321

Merritt, D., & Ferrarese, L., 2001, ApJ, 547, 140

Miralda-Escudé, J. & Kollmeier, J.A., 2003, ApJ, submitted.

Nelson, C.H., 2000, ApJ, 544, L91

Nelson, C.H., & Whittle, M., 1995, ApJS, 99, 67

Nelson, C.H., & Whittle, M., 1995, ApJ, 465, 96

Osterbrock, D.E., & Pogge, R.W., 1985, ApJ, 297, 166

Peterson, B.M., McHardy, I.M., Wilkes, B.J., Berlind, P., Bertram, R., et al., 2000, ApJ, 542, 161

Pounds, K.A., Done, C., & Osborne, J., 1995, MNRAS, 277, L5

Shields, G.A., Gebhardt, K., Salviander, S., Wills, B.J., Xie, B., Brotherton, M.S., Yuan, J., & Dietrich, M., 2003, ApJ, 583, 124

Sulentic, J.W., Zwitter, T., Marziani, P., & Dultzin-Hacyan, D., 2000, ApJ, 536, L5

Thomas, H.-C., Beuermann, K., Reinsch, K.,et al., 1998, A&A, 335, 467

Tremaine, S., Gebhardt, K., Bender, R., et al., 2003, ApJ, 574, 740

Yu, Q., & Tremaine, S., 2002, MNRAS, 335, 965

Voges, W., Aschenbach, B., Boller, T., et al., 1999, A&A, 349, 389

Wandel, A., 1999, ApJ, 519, L39

Wandel, A., 2002, ApJ, 565, 762

Wandel, A., & Boller, T., 1998, A&A, 331, 884

Wang, T., & Lu, Y., 2001, A&A, 377, 52

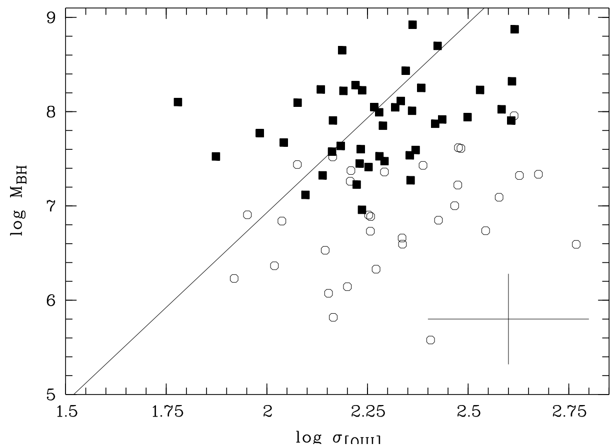


Fig. 1.— Velocity dispersion $\sigma_{[OIII]}$ vs. log $M_{BH}$(H$\beta$). NLS1s are marked as open circles and BLS1s as filled squares. Black hole masses are given in units of $M_{\odot}$. The solid line marks the relation of Tremaine et al. (2003). The cross at the bottom right hand corner represents a typical error bar.

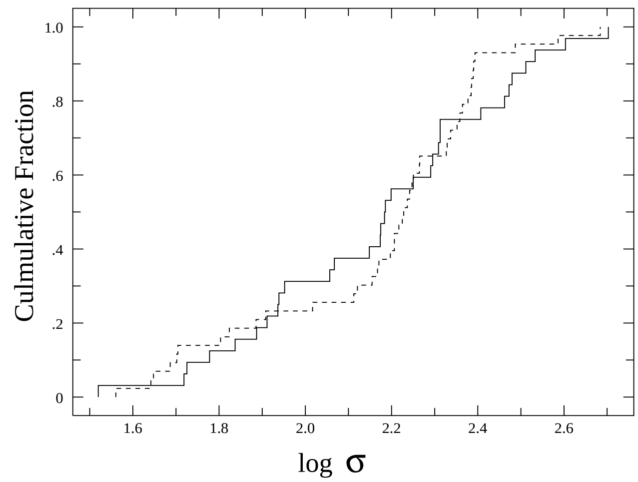


Fig. 3.— Cumulative fraction of a KS test of the distributions of the stellar velocity dispersion $\sigma$ given in units of km s$^{-1}$. The distribution of NLS1s is shown as a solid line and BLS1s are shown as a dashed line.

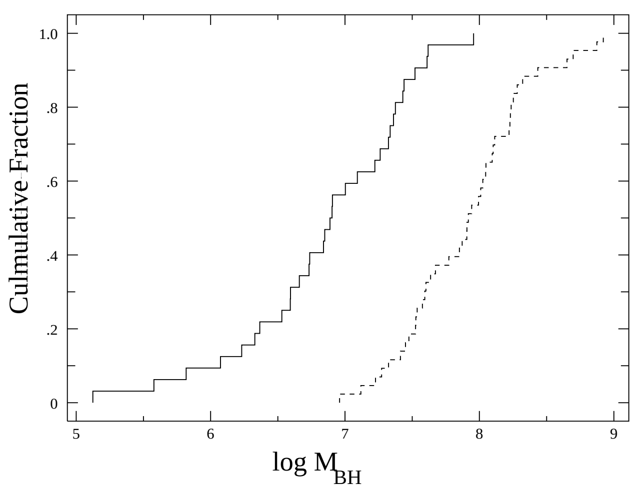


Fig. 2.— Cumulative fraction of a KS test of the black hole mass distributions of NLS1s (solid line) and BLS1s (dashed line) given in units of $M_{\odot}$.

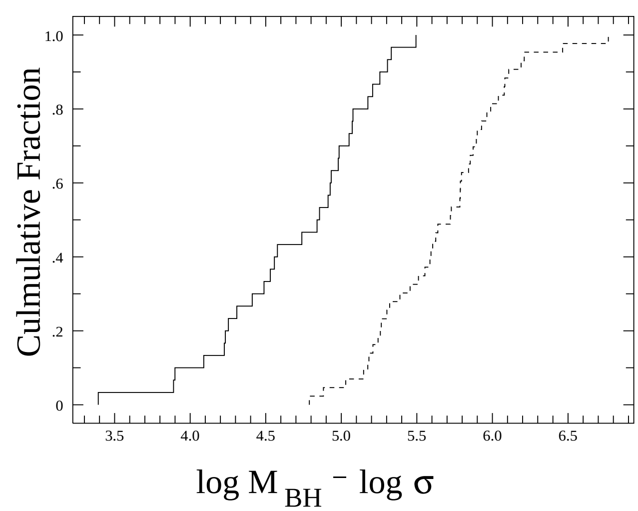


Fig. 4.— Cumulative fraction of a KS test of the distributions of the black hole mass $M_{BH}$ divided by the stellar velocity dispersion $\sigma$. The distribution of NLS1s is shown as a solid line and BLS1s are shown as a dashed line.